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Dredged Material Composting at Milwaukee and Green Bay, WI, Confined Disposal Facilities

PURPOSE: This technical note reports results from demonstration-scale studies of dredged material composting at the Jones Island confined disposal facility (CDF), Milwaukee, WI, and the Bayport CDF, Green Bay, WI. The purpose of these studies was to determine the feasibility of bioremediating dredged material contaminated with polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs). This is the third in a series of technical notes on the feasibility of using low-cost and relatively passive biotechnology to reduce hydrophobic organic chemical concentrations in dredged material. The first technical note (Myers and Bowman 1999) described initial studies at the Milwaukee CDF. The second technical note (Myers and Williford 2000) provided an overview of bioremediation technologies that show promise for practical application to hydrophobic organic compounds in dredged material.

BACKGROUND: Many Great Lakes dredged material CDFs are nearing capacity. Since it is expensive to site, design, and construct new CDFs, alternatives to traditional CDF disposal of dredged material are needed. To address this need, the U.S. Army Engineer District, Detroit, and the Dredging Operations and Environmental Research (DOER) program of the U.S. Army Corps of Engineers partnered with the Great Lakes National Program Office (GLNPO) of the U.S. Environmental Protection Agency to test the feasibility of using composting technology to bioremediate dredged material in CDFs. The larger objective is to convert CDFs from perpetual containment facilities to storage and treatment facilities. If contaminated dredged material can be cost-effectively cleaned to satisfy requirements for beneficial use, perhaps the service life of CDFs can be extended by treating, removing, and beneficially using dredged material.

The effort started in 1998 when wood chips were mixed with dredged material in the Jones Islands CDF (Myers and Bowman 1999). The wood chip/dredged material mixture was mounded, turned, and sampled to determine if contaminant concentrations could be reduced. PCB concentrations decreased over the course of the 2-month study, but PAH concentrations remained unchanged (U.S. Army Engineer District, Detroit, 1999). Apparently, the conditions in the wood chip/dredged material mixture were not right for PAH biodegradation. It was hypothesized that conditions could be improved by adding a readily biodegradable organic carbon source. Plans were then made to expand the effort at the Milwaukee CDF to include biosolids in the wood chip/dredged material mixture and to conduct a similar demonstration project at the Bayport CDF in Green Bay, WI.

SITE DESCRIPTIONS: The Jones Island CDF is located south of the downtown area of Milwaukee, WI (Figure 1). This CDF covers 44 acres (18 ha) along the Lake Michigan shoreline of the south outer Milwaukee Harbor. The Port of Milwaukee is the local sponsor. Among other miscellaneous contaminants, dredged material in the Milwaukee CDF contains PAHs and PCBs. PAHs are the contaminants of primary concern.

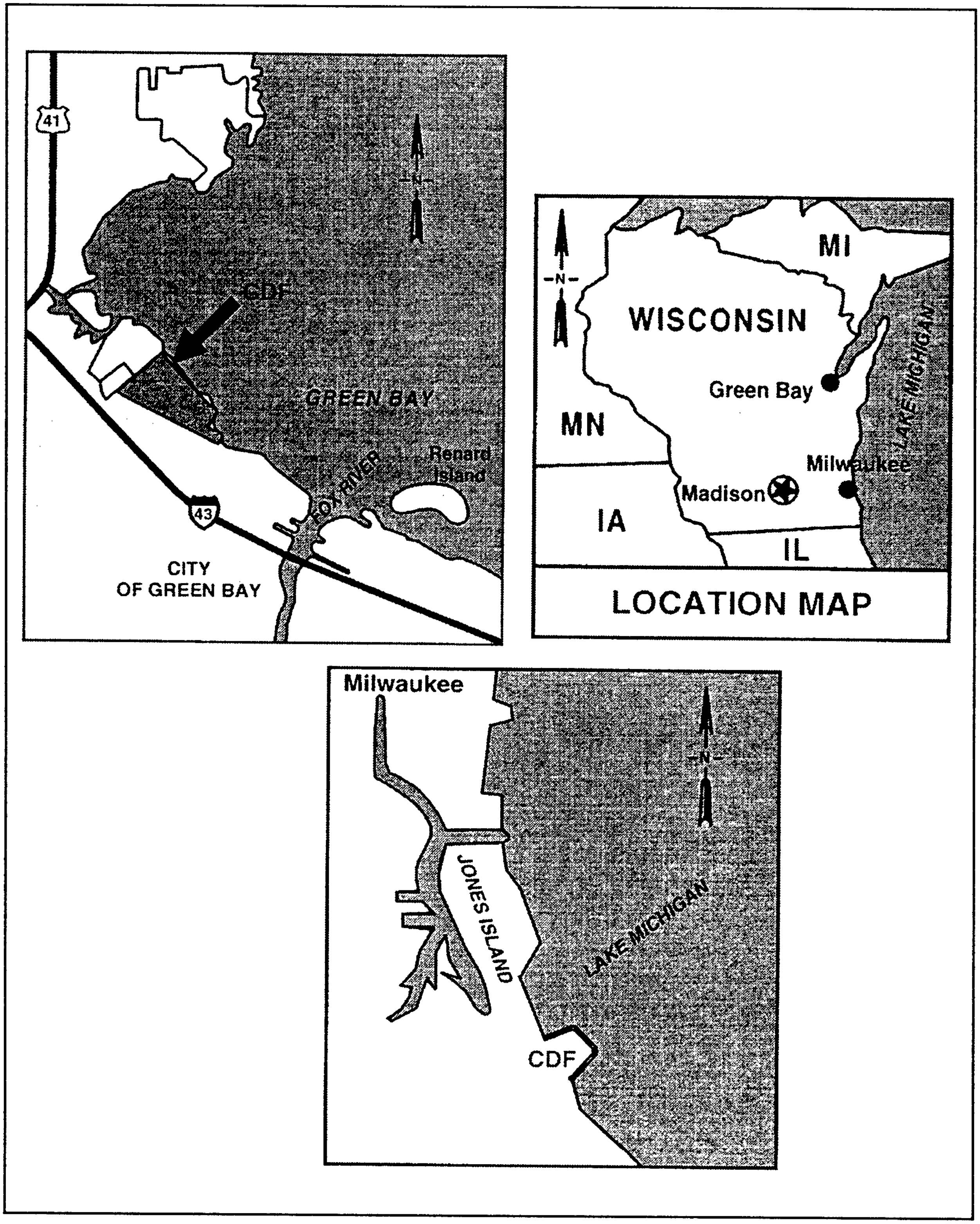

Figure 1. Site vicinity maps

The Bayport CDF is located on the south shore of Green Bay, in the City of Green Bay, WI (Figure 1). The local sponsor is the Brown County Harbor Commission. The Bayport CDF covers 190 acres (77 ha) and is bordered by heavy industry to the east, Chicago and Northwestern Railroad right-of-way to the south, and a natural area to the west. Among other miscellaneous contaminants, dredged material in the Bayport CDF contains PAHs and PCBs. PCBs are the contaminants of primary concern.

MATERIALS, METHODS, AND EQUIPMENT: Mixtures of biosolids, dredged material, and wood chips were placed into four windrows at each CDF. The windrows were constructed in a fashion similar to the windrows previously constructed at the Jones Island CDF (Myers and Bowman 1999). Detailed descriptions are available in U.S. Army Engineer District, Detroit (2001). The ratios of mixture components (by volume) for each windrow are as follows:

Jones Island CDF

- Row 1: 2 biosolids : 2 dredged material : 1 wood chips
- Row 2: 1 biosolids : 2 dredged material : 1 wood chips
- Row 3: 1 biosolids : 2 dredged material : 1 wood chips
- Row 4: 1 biosolids : 2 dredged material : 3 wood chips

Bayport CDF

- Row 1: 1 biosolids : 3 dredged material : 1 wood chips
- Row 2: 3 biosolids : 1 dredged material : 1 wood chips
- Row 3: 2 biosolids : 1 dredged material : 2 wood chips
- Row 4: 2 biosolids : 2 dredged material : 1 wood chips

These ratios are approximate since there was no convenient method to measure the amounts of individual components. At the Jones Island CDF, wood chips derived from storm cleaup were provided by the City of Milwaukee, and biosolids in the form of digested sewage sludge were provided by the Milwaukee Metropolitan Sanitation District. At the Bayport CDF, wood chips were provided by a local pallet company, and biosolids were provided in the form of paunch manure by American Food Industries. Wood chips and biosolids were provided at no cost at both sites.

The Jones Island windrows were constructed atop a wood chip base that covered the entire test area. The windrows were 10 to 12 ft (3.0-3.7 m) wide at the base, 3 ft (0.9 m) high, and 200 ft (61 m) long. At the Bayport CDF, wood chip bases were constructed only for the areas that were covered by each windrow. The windrows were 6-8 ft (1.8-2.4 m) wide at the base, 2 ft (0.6 m) high, and 170 ft (52 m) long. Windrows were aerated and mixed on a weekly basis using a SCAT 481 Turner described in Myers and Bowman (1999). In addition, the windrows were periodically irrigated depending on visual inspection and perceived water content.

During construction, five composite samples each were collected from the biosolids, dredged material, and wood chips stockpiles at each site for chemical analysis for total Kjeldahl nitrogen (TKN), total organic carbon (TOC), total phosphorous (TP), 17 PAHs (naphthalene, acenaphthene, phenanthrene, acenaphthylene, fluorene, anthracene, fluoranthene, chrysene, benzo(b)fluoranthene, pyrene, benzo(a)anthracene, benzo(k)fluoranthene, benzo(a)pyrene, dibenzo(A,H)anthracene, 2-methylnaphthalene, indeno(1,2,3-c,)pyrene, and benzo(G,H,I,)perylene), 7 PCB aroclors, 66 PCB

congeners, and 57 Base-Neutral and Acid extractables (BNAs). After construction, the windrows at each site were monitored weekly for temperature, oxygen, and carbon dioxide. Weekly samples were collected from each windrow for moisture content and pH. On a monthly basis, samples were collected for TKN, TOC, TP, PAH, PCB, and BNA analyses. Initially, BNAs were analyzed, but the initial BNA concentrations were generally below the detection limit, and no further monthly analysis for BNAs was conducted. Each windrow was divided into five equal sections for sampling, and one grab sample was collected for analysis from each subsection on each sampling event. Sampling of windrows at the Jones Island CDF was initiated 8 September 1999, and sampling of the windrows at the Bayport CDF was initiated on 9 September 1999. Windrow turning and sampling was conducted for 3 months.

Snell Environmental Group, Inc., Lansing, MI, conducted all field sampling activities including weekly temperature, oxygen, and carbon dioxide measurements and laboratory analysis for moisture content and pH. DZL Laboratories, Inc., Lansing, MI, conducted laboratory analysis of monthly samples for TKN, TOC, and TP. The Environmental Chemistry Branch, U.S. Army Engineer Research and Development Center, Vicksburg, MS, conducted laboratory analysis of PCBs, PAHs, and BNAs. All sample collection, handling, chain-of-custody, and analysis complied with the Quality Assurance Project Plan approved by GLNPO for this study.

RESULTS: Detailed results, excluding temperature, oxygen, and carbon dioxide, are not presented in this technical note due to the extensive amount of data collected. Averages for pH, moisture content, TKN, TOC, and TP are described. As previously stated, BNAs were generally below the detection limit and therefore are not presented. The PAH data are presented as total PAH in tabular form and in graphical form as summed individual PAHs. The PCB aroclor data are not presented, and the PCB congener data are presented as total PCB in tabular form and in graphical form as summed homolog groups (PCB congeners with the same number of chlorine atoms). Detailed results are available in U.S. Army Engineer District, Detroit (2001).

Chemical Analysis of Compost Material Components. TKN, TOC, and TP concentrations in dredged materials, biosolids, and wood chips used in the composting projects at the Jones Island and Bayport CDFs are listed in Table 1. Total PCB and total PAH concentrations are listed in Table 2. As expected, the biosolids provided the majority of the nitrogen and phosphorus in the compost mixes, and the dredged material, compared with the biosolids and wood chips, provided little organic matter to the compost mixes.

As expected, total PCB concentration in the dredged material at the Bayport CDF was higher than that in the dredged material at the Jones Island CDF. Also as expected, total PCB concentrations in the biosolids and wood chips at the Bayport site were low; that is, the dredged material contributed most of the PCB mass to the compost mix. Unexpectedly, the biosolids and wood chips at the Jones Island site contained about as much PCB as did the dredged material.

As expected, total PAH concentrations were much higher in dredged material from the Jones Island CDF than in dredged material from the Bayport CDF. However, the total PAH concentrations in the biosolids at the Jones Island site were unexpectedly high. The biosolids total PAH concentration was 42 percent of the total PAH concentration in the dredged material, and the total PAH

concentration in the wood chips at the Jones Island site was greater than the total PAH concentrations in biosolids at the Bayport site.

Table 1
Mean (Standard Deviation) TKN, TOC, and TP Concentrations in Compost Materials (from U.S. Army Engineer District, Detroit, 2001)

Parameter	Wood Chips	Biosolids	Dredged Material
Jones Island CDF, Milwaukee, WI			
TKN (mg/kg)	3,300 (1,220)	8,920 (7,240)	1,220 (610)
TOC (g/kg)	166 (42)	143 (370)	24 (13)
TP (mg/kg)	200 (42)	2,380 (286)	358 (215)
Bayport CDF, Green Bay, WI			
TKN (mg/kg)	1,330 (519)	13,700 (6,650)	3,160 (635)
TOC (g/kg)	136 (6)	250 (67)	37 (9)
TP (mg/kg)	61 (17)	2,120 (402)	704 (66)

Note: Mean = average of five samples.

Table 2
Mean (Standard Deviation) Total PAH and Total PCB Concentrations in Compost Material

	Jones Island		Bayport	
	tPAH, mg/kg	tPCB, μg/kg	tPAH, mg/kg	tPCB, μg/kg
Dredged material	62.7 (59.0)	219 (101)	3.3 (0.8)	1,221 (41)
Biosolids	26.2 (2.6)	244 (61)	0.4 (0.2)	35 (18)
Wood chips	3.4 (5.9)	127 (73)	0.2 (0.09)	55 (16)

Note: Mean = average of five samples, Total PAH = sum of 17 PAHs, Total PCB = sum of 66 PCB congeners.

General Compost Parameters. Temperatures in the Jones Island windrows peaked in the second to third week of operation (Figure 2a). Oxygen minima and carbon dioxide maxima were observed in the second week (Figures 2b and 2c, respectively). These data show that maximum biological activity took place during the second and third weeks of operation. Thereafter, the indicative parameters of biological activity declined to the point that the windrows were relatively static by Week 12. Temperatures in the Jones Island windrows were below the thermophilic range (54-65 °C) conducive to composting throughout the entire study period. For about the first 3 weeks, temperatures in Windrows 1 and 4 were near the thermophilic range. Periodic addition of biosolids is apparently required to maintain optimum temperature conditions for composting.

The Bayport windrows were relatively inactive in comparison to the Jones Island windrows. Windrow temperatures were much lower; oxygen concentrations were higher; and carbon dioxide concentrations were lower than in the Jones Island windrows. In the Bayport windrows, there was no rapid increase in temperature (Figure 3a), or decline in oxygen (Figure 3b), or increase in carbon dioxide (Figure 3c). A slight increase in biological activity between weeks 6 and 8 was indicated

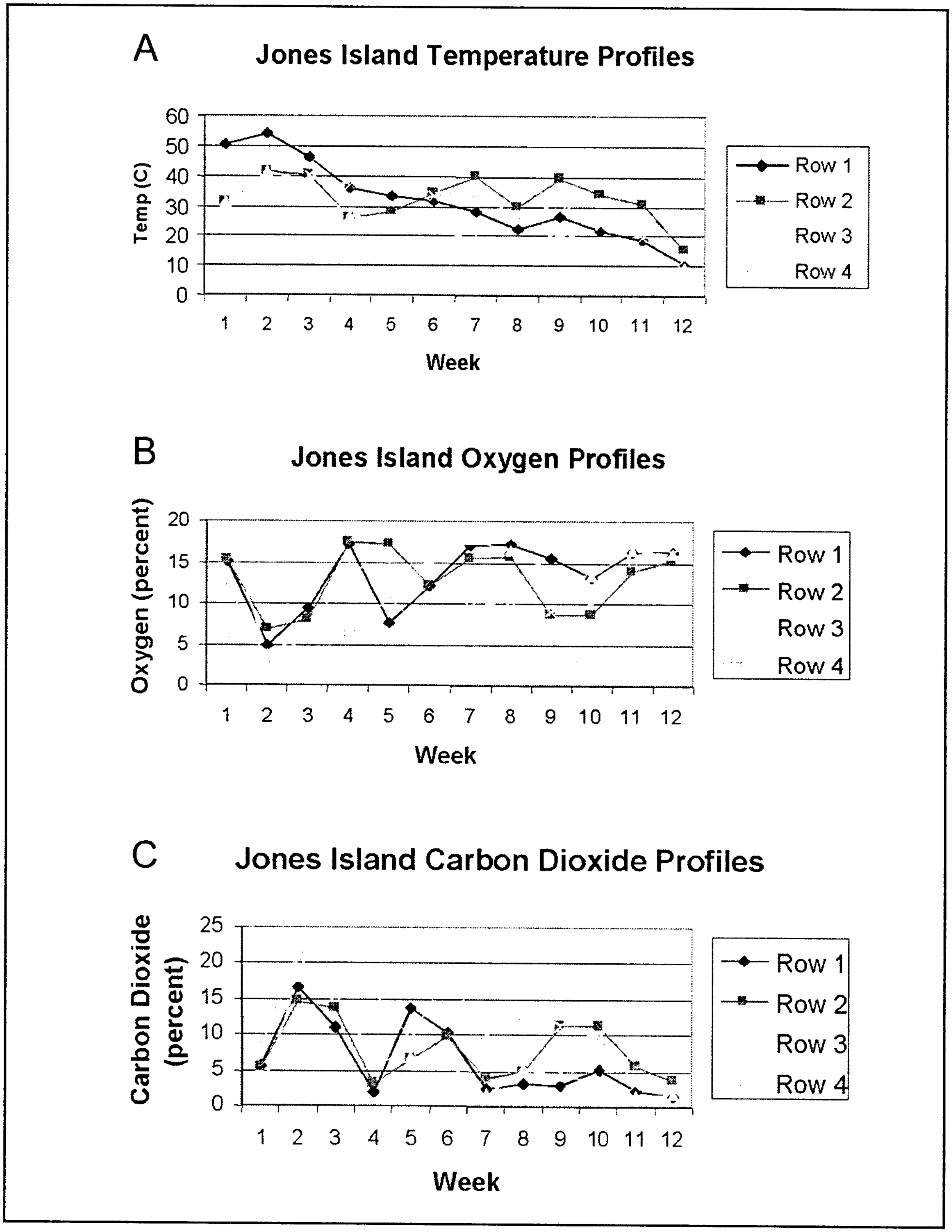

Figure 2. Jones Island windrows

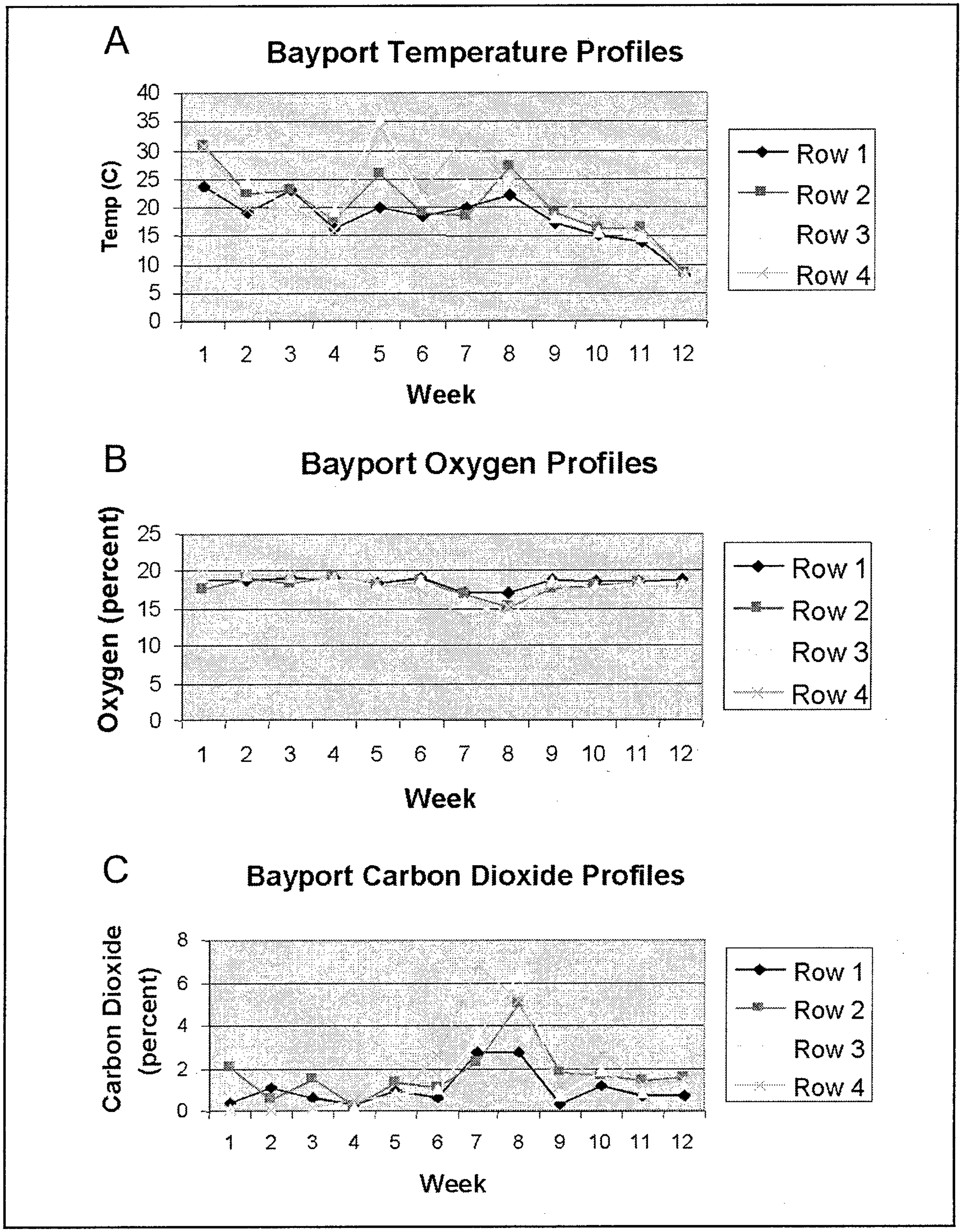

Figure 3. Bayport windrows

in the oxygen and carbon dioxide profiles for all four windrows. The smaller size of the windrows at the Bayport CDF and more northern latitude of this CDF relative to the Jones Island windrow size and latitude may account for the differences in indicators of biological activity.

Moisture content (weight of water/total weight) averaged 0.22 to 0.32 in the Jones Island windrows and 0.19 to 0.21 in the Bayport windrows. There were no distinct trends in moisture content in the windrows at either site during the study. Fahnestock et al. (1998) recommend keeping the water content between 40 and 85 percent of the field capacity of the soil to be bioremediated. Silt and clay soils, typical of fine-grain dredged material such as in the Bayport and Jones Island CDFs, usually have a field capacity (reported as weight water/weight dry solids) of around 0.25-0.40, and high organic matter such as biosolids can exceed 1.0 (Meriaux 1982). The moisture contents in the windrows at the Jones Island and Bayport CDFs, when converted to water content defined as weight water/weight dry solids, ranged from 0.23-0.47. The actual field capacities of the dredged material in the Bayport and Jones Island CDF are not known, but the range indicated for fine-grain soils is a reasonable approximation. Thus, the windrows may have been wetted to the recommended levels for composting.

The pH of the compost windrows at both sites averaged pH 7.3 to 7.4. These values are in the range suitable for biological activity. There were no distinct trends in pH in the windrows at either site during the study.

TKN, TP, and TOC in the Jones Island windrows (Table 3) were highly variable over time. In general, TKN concentrations were lower at the end of the study than at the beginning. Windrow 1, which had the highest percentage biosolids, was the only windrow in which TKN consistently declined with time. In the other windrows, the samples collected after 1 month of composting showed higher TKN than the initial sample. TOC was also highly variable with three of four windrows showing higher concentrations at the end of the study than at the beginning. Again, Windrow 1 was the exception. TOC in this windrow consistently decreased during the study. There was a significant increase in TP in the Jones Island windrows over the first month of operation. Thereafter, TP was highly variable.

TKN, TP, and TOC in the Bayport windrows (Table 4) were also highly variable over time. In general, TKN concentrations were lower at the end of the study than at the beginning with the highest rate of decrease occurring between month 1 and month 2. Month 1 to month 2 was also the time period for the highest rate of carbon dioxide generation (Figure 3c). No consistent trends in TOC could be identified. (The 1-month and 2-month TOC entries for Windrow 2 are not mistakes. The replicate samples were quite different for the two sampling events; however, the means and standard deviations, after round off, were the same.) As was the case with the Jones Island windrows, there was a significant increase in TP in the Bayport windrows over the first month of operation. The TP concentrations were higher at the end of the study than at the beginning.

Since TKN, TOC, and TP concentrations in the components of the compost mix at both sites were highly variable (Table 1), it is not surprising that the compost at each site was also highly variable in terms of TKN, TOC, and TP at each sampling event. Although the data are highly variable, a decrease in TKN is evident from a comparison of TKN concentrations in the compost at both sites after 3 months with the initial TKN concentrations in the compost components (Table 1). TKN

Table 3
Jones Island Compost Windrows Average (Standard Deviation) TKN, TOC, and TP Concentrations (from U.S. Army Engineer District, Detroit, 2001)

Parameter	Initial	1 Month	2 Months	3 Months
Windrow 1				
TKN (mg/kg)	8,580 (3,550)	6,608 (1,450)	1,280 (349)	808 (116)
TOC (g/kg)	105 (35)	60 (16)	53 (8)	36 (5)
TP (mg/kg)	2,080 (349)	6,274 (2,000)	2,680 (779)	4,900 (212)
Windrow 2				
TKN (mg/kg)	988 (405)	3,270 (2,320)	1,230 (261)	580 (72)
TOC (g/kg)	15 (5)	24 (10)	39 (7)	28 (6)
TP (mg/kg)	262 (86)	2,550 (1,980)	762 (318)	1,480 (623)
Windrow 3				
TKN (mg/kg)	750 (157)	3,070 (1,130)	1,360 (207)	590 (110)
TOC (g/kg)	14 (4)	29 (7)	26 (3)	25 (5)
TP (mg/kg)	218 (119)	2,720 (1,290)	906 (224)	1,520 (44)
Windrow 4				
TKN (mg/kg)	1,730 (1,050)	3,660 (1,080)	1,080 (312)	614 (109)
TOC (g/kg)	20 (10)	29 (5)	35 (6)	25 (4)
TP (mg/kg)	562 (456)	2,340 (561)	808 (430)	1,320 (389)

Note: Average of 5 samples from each windrow, each sample taken from a specific subsection of the windrow.

Table 4
Bayport Compost Windrows Average (Standard Deviation) TKN, TOC, and TP Concentrations (from U.S. Army Engineer District, Detroit, 2001)

Parameter	Initial	1 Month	2 Months	3 Months
Windrow 1				
TKN (mg/kg)	3,860 (940)	4,110 (783)	552 (115)	494 (108)
TOC (g/kg)	42 (9)	71 (37)	79 (15)	44 (7)
TP (mg/kg)	352 (24)	1,080 (124)	558 (178)	600 (148)
Windrow 2				
TKN (mg/kg)	4,060 (780)	5,510 (4,670)	524 (119)	374 (71)
TOC (g/kg)	79 (48)	70 (35)	70 (35)	50 (6)
TP (mg/kg)	336 (27)	2,510 (2,490)	684 (294)	810 (254)
Windrow 3				
TKN (mg/kg)	4,460 (404)	4,500 (145)	544 (114)	506 (57)
TOC (g/kg)	50 (11)	59 (16)	71 (17)	45 (10)
TP (mg/kg)	344 (13)	1,110 (121)	580 (158)	758 (205)
Windrow 4				
TKN (mg/kg)	4,160 (1,220)	3,720 (2,080)	460 (72)	498 (64)
TOC (g/kg)	52 (9)	48 (12)	87 (9)	44 (18)
TP (mg/kg)	368 (126)	1,159 (98)	748 (23)	824 (79)

Note: Average of 5 samples from each windrow, each sample taken from a specific subsection of the windrow.

concentrations after 3 months of composting were less than the initial TKN concentrations in any of the compost constituents. TOC concentrations after 3 months of composting were much less than the initial TOC concentrations in the wood chips and biosolids and about the same as the TOC concentration in the dredged material.

PAHs: PAH concentrations in the windrows at the Jones Island and Bayport CDFs are shown in Figures 4 and 5, respectively. In each bar in the graphs, the individual PAH concentrations are stacked so that the height of the bar represents the total PAH concentration. The bars are grouped into four major groups with four bars in each group. The major groups represent separate windrows, and the bars within each major group are labeled according to collection time and windrow number. The lack of a distinct decrease in PAH concentrations from the initial values in the Jones Island windrows over the 3-month study was a disappointing result that is discussed in more detail later.

The mean PAH concentrations in Windrows 2 and 4 at the Bayport CDF decreased in a monotonic fashion with decreases of 30 and 35 percent, respectively. As is discussed later, statistical analysis showed that these declines in mean concentrations were not significant.

PCBs: PCB concentrations in the windrows at the Jones Island and Bayport CDFs are shown in Figures 6 and 7, respectively. The graphs are organized and labeled as previously described for the PAH graphs. Less-than values were assigned a value of one-half the detection limit. PCB homolog concentrations are stacked in each bar so that the height of each bar represents a total PCB concentration. (A homolog is the sum of the PCB congeners with the same number of chlorine atoms, e.g., homolog 3 is the sum of the trichlorobiphenyl congener concentrations.) Figure 6 shows that the ending PCB concentrations were lower than the initial PCB concentrations in the Jones Island windrows. However, the lowest concentrations were measured after 1 month of composting (except Windrow 2), and then the concentrations tended to increase. PCB concentrations in the Bayport windrows (Figure 7) were highly variable and showed no significant change in PCB concentrations in response to composting with biosolids and wood chips. All the Bayport windrows showed the same pattern with the lowest PCB concentration in the 2-month (November) sample.

DISCUSSION: Three topics are discussed in this section as follows: variability in the data, statistical analysis of the data, and the implications of studies conducted on sediments and dredged material from Milwaukee, WI, by others.

Variability. The results from both sites were highly variable as indicated by the standard deviations listed in the tables and the error bars in the graphs. Furthermore, there were inconsistencies in the data that cannot be simply explained as random variation. For example, TP concentrations at both sites and in all windrows were much lower initially than in the 1-month samples. Another example is the tendency for PCB concentrations to increase in the Jones Island windrows beginning with the 1-month sample. Large variance combined with inconsistencies make it difficult to draw firm conclusions from the data. The following discussion attempts to explain some of the inconsistencies, beginning first with a discussion of variance in the data.

Sources of variance in the data include the following:

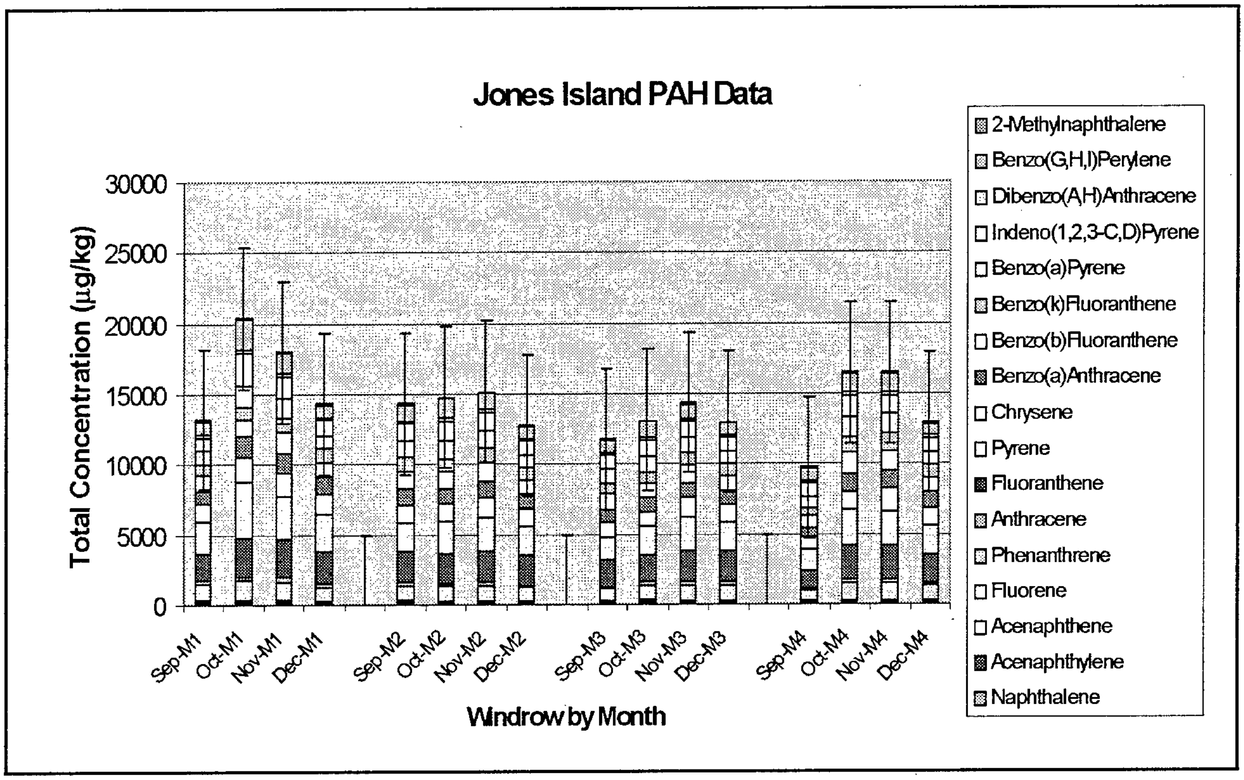

Figure 4. Average PAH concentrations in Jones Island windrows (n = 5, error bars are one standard deviation, Sep is initial)

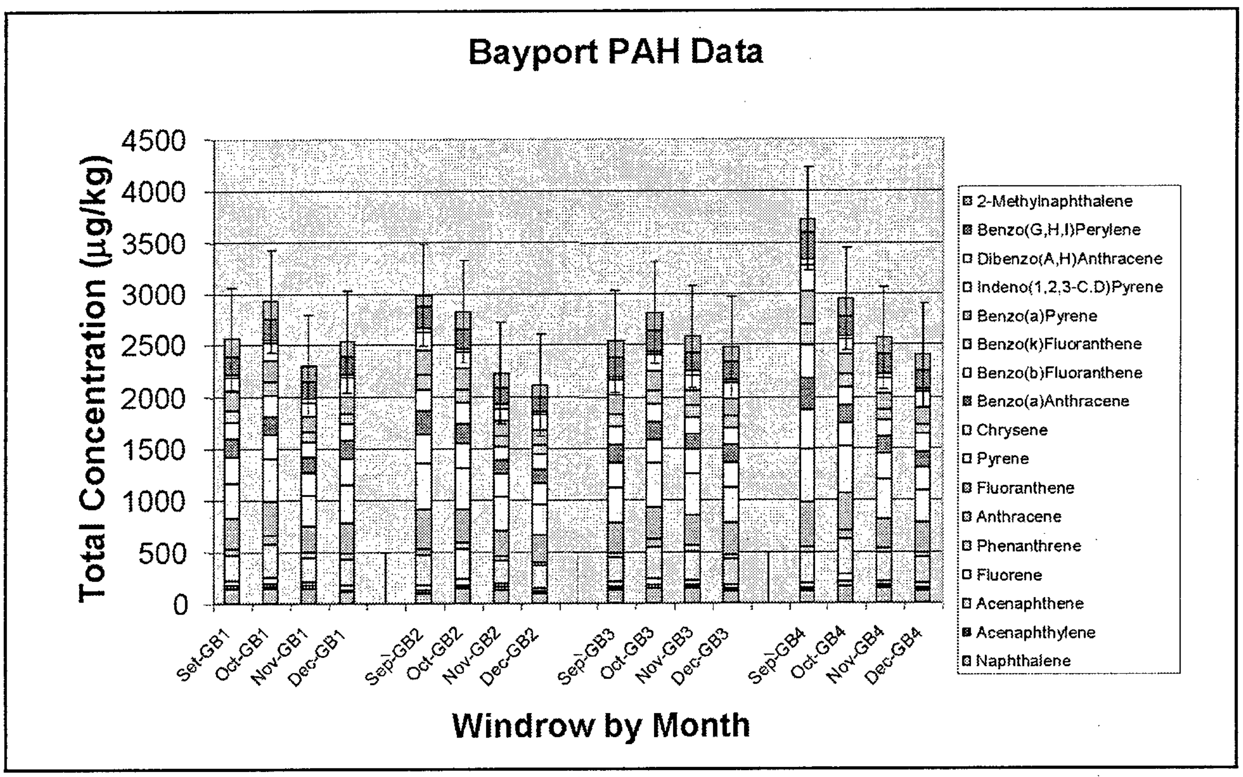

Figure 5. Average PAH concentrations in Bayport windrows (n = 5, error bars are one standard deviation, Sep is initial

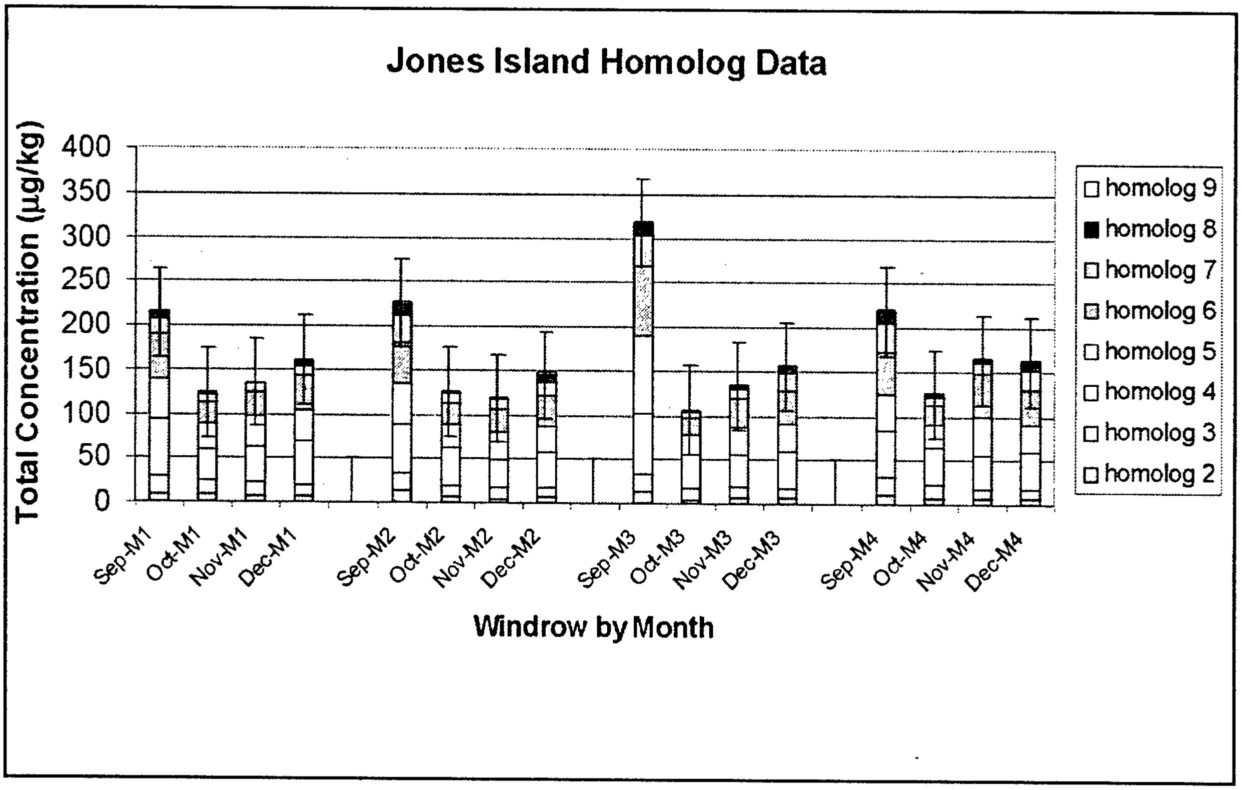

Figure 6. PCB homolog concentrations in Jones Island windrows (n = 5, error bars are one standard deviation, Sep is initial)

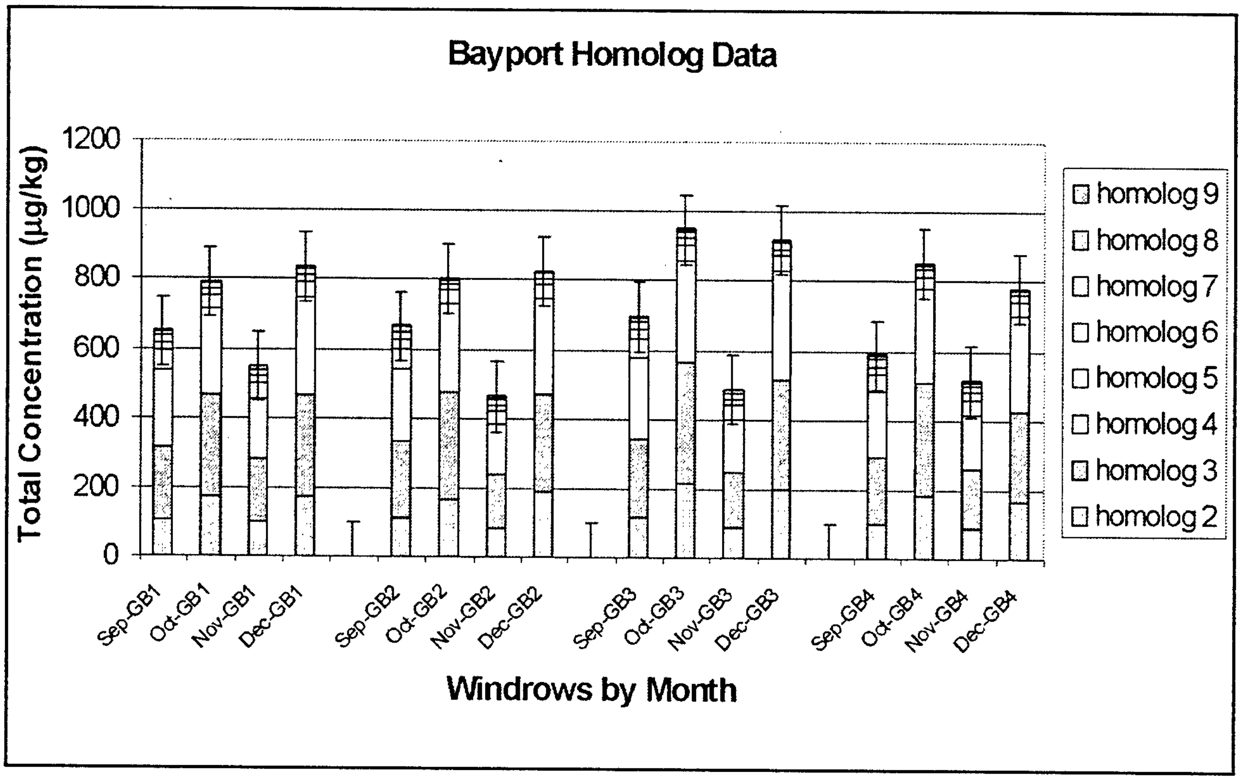

Figure 7. PCB homolog concentrations in Bayport windrows (n = 5, error bars are one standard deviation, Sep is initial)

- Variability of the compost materials. The data in Tables 1 and 2 show that the compost materials were highly variable in terms of chemical parameters.
- Variations in mixing. It is reasonable to expect that on any given day, the turner does not mix all windrows equally or completely.
- Sampling variability. It was difficult to collect a representative sample of compost, especially at the beginning of the study when there were three distinct materials in the compost. At the end of the study when the wood chips had broken down and the biosolids had become more or less incorporated into the dredged material, a more representative sample could be collected.
- Analytical variability. TKN, TOC, and TP analyses require a digestion step, and PAH and PCB analyses require an extraction step. The analyst was faced with taking a representative subsample for digestion or extraction because the digestion or extraction vessel was smaller than the sample. In addition, PAH and PCB analyses are known to be highly variable even on standard solutions and especially at the low concentrations measured in this study. TKN, TOC, and TP analyses also are not without some variability in the finishing analytical technique.

Highly variable results are therefore to be expected. However, distinct trends that are inconsistent with conservation of mass were not expected. The increases in TP from initial concentrations to the 1-month TP concentrations were really surprising even with all the sources of variability that affected the results. There are no internal or known external sources of phosphorus that could have caused this increase. TP should have stayed relatively constant or decreased during the study. Leaching could cause a decrease in TP concentrations but not an increase. If losses by leaching are neglected, TP should behave as a conservative tracer, especially over the first month of operation when cumulative leaching losses were the lowest.

Assuming that TP can be treated as a conservative tracer, TP was used to evaluate mixing of the compost windrows. In order to use TP in this manner, TP data were normalized by dividing the average TP concentrations in Tables 3 and 4 by the average TP concentration in the dredged material from Table 1. The results are presented in Table 5.

The normalized TPs in the initial samples from the windrows at both the Jones Island and Bayport CDFs were lower than in the 1-, 2-, and 3-month samples that followed. This may indicate inadequate mixing before the first samples were taken or collection of samples deficient in biosolids. Comparison of initial normalized TP to the 3-month normalized TP, assuming that at 3 months the windrows were approaching the maximum mixing that was going to be achieved, suggest that the Bayport windrows were better mixed than the Jones Island windrows. Initial and 3-month normalized TPs at Jones Island differed by factors of 2 to 7, while the initial and 3-month normalized TPs at Bayport differed by factors of about 2 to 2.5. Since the Bayport windrows were smaller than the Jones Island windrows, it is reasonable to expect better mixing of windrows at the Bayport CDF.

The normalized TPs for Windrow 1 at the Jones Island CDF were higher than for the other windrows, as expected since Windrow 1 contained more biosolids than the other windrows. The high biosolids

Table 5
Normalized TP

Windrow	Initial	1-Month	2-Month	3-Month
Jones Island				
1	5.81	17.83	7.49	13.69
2	0.73	7.12	2.13	4.13
3	0.61	7.60	2.53	4.25
4	1.57	6.54	2.26	3.69
Bayport				
1	0.50	1.53	0.79	0.85
2	0.48	3.57	0.97	1.15
3	0.49	1.58	0.82	1.08
4	0.52	1.65	1.06	1.17

Note: Normalized TP: compost TP/dredged material TP.

content for Windrow 1 might also explain why TKN and TOC behavior with time in Windrow 1 was different from the other windrows.

Statistical Analysis. The variability in the data makes it extremely difficult to determine if PAH or PCB degradation occurred during composting. It is possible that there was some disappearance of PAHs and PCBs that was obscured by all the variability in the data. Analysis of variance (ANOVA) (Glantz 1997) statistical techniques were used to separate differences attributable to random variation from differences that may be attributable to contaminant degradation and removal processes or other nonrandom sources of variation.

One-way ANOVAs were conducted by windrow to test for significant differences between mean contaminant concentrations with sampling time. Replicates were included in the analysis, and the level of significance was 0.05. In some comparisons, the statistical tests for normality and equality of variance were rejected. In these cases, a nonparametric one-way ANOVA, Kruskal-Wallis on ranks (Glantz 1997), was conducted. A one-way ANOVA tests the global hypothesis that all the samples from a given windrow were drawn from a single population, that is, time had no effect. The results are shown in Table 6. The "Yes" entries in Table 6 indicate that the differences in mean values were greater than would be expected by chance; that is, there were statistically significant differences ($p < 0.05$) among the samples collected at different times. ANOVA showed significant differences for most of the PCB data and nonsignificance for most of the PAH data.

ANOVA only tests the global hypothesis that all the means were from a single population. It does not provide information on which mean or means differed from the others. In those cases where the one-way ANOVA indicated that the means were not from a single population, a statistical procedure for multiple pair-wise comparison of all means, Tukey test (Glantz 1997), was conducted.

The Tukey test showed that the initial mean (Sep) differed significantly from the subsequent means including the final mean (Dec) for tPCB in Windrows 1-3 at the Jones Island CDF. For Window 4 at

Table 6
One-Way ANOVA of PCB and PAH Data

CDF	Windrow	Significance	
		PCB	PAH
Jones Island	1	Yes	No
	2	Yes	No
	3	Yes	No
	4	Yes	Yes
Bayport	1	Yes	Yes
	2	Yes	No
	3	Yes	No
	4	No	No

Note: "Yes" indicates statistically significant differences among means at $p < 0.05$.

the Jones Island CDF, the Tukey test showed a significant difference between the initial (Sep) mean and the 1-month (Oct) mean. However, the difference between the initial tPCB mean in Windrow 4 at the Jones Island CDF and the 2- and 3-month (Nov and Dec, respectively) tPCB was not significant. Figure 6 shows that initial tPCB in the Jones Island windrows was higher than any of the other tPCB values. Thus, at the Jones Island CDF there was a statistically significant decline in tPCB in Windrows 1-3, but not Windrow 4. The reductions in tPCB between initial and final were 25, 35, and 51 percent for Windrows 1, 2, and 3, respectively. Decreases occurred across all homolog groups with substantial decreases in the tetra, penta, and hexa homologs. Disappearance of these more chlorinated PCBs, which are not very volatile, implies that volatilization was not the primary loss mechanism. The previous effort to compost dredged material at the Jones Island CDF using only wood chips showed a 55 percent reduction in tPCB (U.S. Army Engineer District, Detroit, 1999). Apparently the addition of biosolids to the compost mixture did not enhance disappearance of PCBs.

The Tukey test for the Bayport tPCB data showed that the 2-month (Nov) mean for Windrows 1-3 was significantly different from the 1- and 3-month (Oct and Dec, respectively) means. However, the 2-month (Nov) mean was the lowest tPCB concentration measured in all four windrows (Figure 7). According to the Tukey test, the low concentrations measured in November were not due to random chance. Some factor such as poor mixing caused the low values. More importantly, the Tukey test showed that the initial and final tPCB concentrations in Windrows 1 and 3 were not significantly different. The one-way ANOVA showed no significant differences in the mean tPCB concentrations for Windrow 4. In the one case (Windrow 2) where the Tukey test showed a significant difference between initial and final tPCB mean concentrations, the initial concentration was lower than the final concentration. Thus, the statistical analyses confirmed what is obvious from inspection of Figure 7: there was no decrease in tPCB concentrations in the compost windrows at the Bayport CDF.

This statistical analysis showed significant disappearance of PCBs at Jones Island and not at the Bayport CDF. Yet, PCBs were the contaminant of concern at Bayport, not Jones Island. The

composting demonstrations at Jones Island and Bayport differed in several ways. Wood chips, biosolids, dredged material, and size of the compost heaps differed. Biological activity as indicated by temperature, oxygen, and carbon dioxide concentrations differed. The difference in compost biological activity was probably the primary reason PCB treatment effectiveness was so different. The differences in size and perhaps latitude probably affected the ability of the compost windrows to retain heat. This in turn affected biological activity. The differences in the source of biosolids may have played a role also.

One-way ANOVA (Table 6) showed that at the Jones Island CDF only Windrow 4 contained significant differences among the mean tPAH values. The Tukey test showed that the initial mean for Windrow 4 was significantly different from the October and November means, but not the December mean. Since the initial mean was lower than any of the other means, the differences that were significant cannot mean PAH disappearance or biodegradation. At the Bayport CDF there were significant differences in mean tPAH for Windrow 1 only. The Tukey test showed that there was a significant difference between October and November means only. The differences in mean tPAH concentrations for October and November cannot be taken to imply PAH disappearance or biodegradation because there was no significant difference between October and December or November and December and most importantly between initial and final mean tPAH concentrations. Overall, statistical analysis showed that there was no statistically significant reduction in tPAH concentrations in either the Jones Island or the Bayport compost windrows.

Work of Others. Information from two separate and independent investigations may help explain some of the disappointing results reported in this technical note.

Sayles et al. (2001) showed that addition of biosolids to sediment from the Kinnickinnic River, which drains into the Milwaukee Harbor, inhibited PCB disappearance in bench-scale land treatment studies. Biosolids from a sewage treatment plant in Cincinnati, OH, were mixed in various amounts with Kinnickinnic River sediment. The inhibition of PCB disappearance was nearly linear with the amount of biosolids added. The Sayles et al. (2001) work is consistent with the field demonstrations conducted at the Jones Island CDF. Composting without biosolids at the Jones Island CDF (U.S. Army Engineer District, Detroit, 1999), reduced PCB concentrations more than composting with biosolids (described in the present technical note). Two explanations are possible for the biosolids effect. First, biosolids can reduce volatile emissions of hydrophobic organic compounds by sorbing gas phase chemical (Hsu et al., 1993; Gan et al., 1998). This explanation implies that the previously reported disappearance of PCBs from the wood-chip-only compost at the Jones Island CDF was due to volatilization. However as previously noted, the disappearance of the more chlorinated PCBs is not consistent with the volatilization explanation. Another explanation is that the microbes preferentially used the most readily available source of carbon and energy; that is, the microbes switched from degrading PCBs to degrading the biosolids.

Ghosh et al. (2000) and Talley, Ghosh, and Luthy (2001) showed that dredged material from the Jones Island CDF contains two distinct sediment fractions that are separable by gravity—light (coal) and heavy (sand/silt/clays). The light fraction accounted for only 5 percent of the total weight but 62 percent of the total PAHs. Thermal programmed desorption-mass spectrometry showed low mobility of the PAHs associated with the coal particles and relatively high mobility of the PAHs associated with the sand/silt/clay fraction. Thus, dredged material in the Jones Island CDF contains

distinct particle types with different concentrations and binding of PAHs. PAHs on the sand/silt/clay fraction, about 38 percent, may be biotreatable. However, the PAHs on coal-derived particles are probably not bioavailable and hence not biotreatable.

With less than 40 percent of the PAHs in Jones Island dredged material potentially biotreatable, it is very difficult to demonstrate treatment with highly heterogeneous compost. The extent of treatment probably needs to be substantially greater than 40 percent in order to overcome the variability in the compost materials. In the short time of this study, this degree of treatment for PAHs is usually not feasible with composting technology (Fahnestock et al. 1998).

CONCLUSIONS: Composting for 3 months in the fall of the year was not effective in remediating contaminants of concern in dredged material from Federal navigation channels in Green Bay and Milwaukee, WI. PAHs in dredged material, in particular, are resistant to bioremediation with composting technology. PCBs may be susceptible to remediation with composting technology as was demonstrated at the Jones Island CDF in Milwaukee, WI, but the factors and conditions that favor PCB biodegradation are not well understood, as was demonstrated by the failure of composting to reduce PCB concentrations at the Bayport CDF, Green Bay, WI. Composting dredged material with wood chips is more effective in reducing PCB concentrations than composting with wood chips and biosolids. The biosolids effect may reflect a reduction in volatile emission of PCBs due to sorption by the biosolids or could be due to a microbial preference for biosolids versus PCBs, or both.

Mixtures of dredged material, biosolids, and wood chips are highly heterogeneous, and this heterogeneity makes it difficult to properly characterize the chemical composition of the mix, especially the initial chemical composition. This heterogeneity also makes it difficult to demonstrate treatment effectiveness, especially if the treatment effect is small. The extent of reaction must exceed the inherent variability of composted dredged material. This is probably not possible in short-term studies during cool months with PAH-contaminated dredged material and passive composting technology, such as used in this study. The size of the compost heap and ambient temperature affect the temperature maintained in the compost heap and thereby affect treatment effectiveness. Short-term dredged material composting is more likely to be successful if conducted during the summer and with large heaps.

Additional research on management and control of compost heaps as well as process optimization will be needed before composting technology can be used to effectively reduce hydrophobic organic contamination in dredged material. Heap size and the level and frequency of biosolids addition are factors that need to be optimized. With additional work in these areas, composting technology could become a valuable tool for treating dredged material in CDFs and then recovering storage capacity by beneficially using treated dredged material.

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Myers, T. E., Bowman, D.W., and Myers, K. F. (2003). "Dredged material composting at Milwaukee and Green Bay, WI, confined disposal facilities," *DOER Technical Notes Collection* (ERDC TN-DOER-C33), U.S. Army Engineer Research and Development Center, Vicksburg, MS *www.erdc.army.mil/el/dots/doer*

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